Improvement of the Cloud Physics Formulation in the U.S. Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

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LONG-TERM GOALS

Correct representation of cloud processes is critical in producing accurate numerical weather prediction (NWP) forecasts. The major goal of the project is to develop state of the art parameterizations of cloud processes and implement them into COAMPS.

OBJECTIVES

Accurately representing cloud processes over a mesoscale model grid volume is currently hindered by inadequate representation of aerosol-cloud microstructure interactions. To resolve these present model shortcomings, we are developing a comprehensive formulation of cloud-aerosol interactions which will include parameterizations of droplet nucleation processes and the effects of giant aerosols. We are expanding our efforts to investigate these aerosol-cloud-precipitation interactions for cumuliform clouds and are developing methodologies for the verification of parameterizations against a variety of observational datasets.

APPROACH

Our accomplishments in previous years centered on the effects of precipitation on boundary layer structure and mesoscale geometry (Mechem and Kogan 2003) in COAMPS. Employing the same microphysical framework, we recently explored how these precipitation processes in turn influence CCN characteristics (Mechem et al. 2006). Strong drizzle can significantly deplete the CCN population, which can lead to even more efficient precipitation production in subsequent cloud cycles. COAMPS is able to represent this process, even in a relatively simple bulk microphysical framework. Results agree reasonably well with LES and scalings of cloud processing derived from theory and in-situ aircraft data. Mechem et al. (2006) investigated cloud processing in context of other boundary layer source and sink terms for the ultimate purpose of an accurate mesoscale forecast of the aerosol-cloud-drizzle system.

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Because of the fidelity and wide popularity of the bulk drizzle parameterization now used in COAMPS, we have turned our efforts to more thoroughly representing the cloud response to aerosol characteristics. We are exploring how to represent droplet nucleation beyond the simple diagnostic relations previously employed. Large eddy simulation (LES) with size resolving microphysics is employed for this purpose and represents the full interaction of 3D dynamics and microphysics. LES suggests important aspects of aerosol activation not captured by nucleation schemes based on simple nonentraining plume models typically used to derive these relations.

In addition to developing a nucleation parameterization for use in a bulk microphysical framework, our previous work demonstrated the importance of including giant CCN (GCCN) with radii greater than 1 μm. We have performed further tests of the GCCN parameterization in an LES framework by evaluating the sensitivity of cloud radiative properties to changes in GCCN and background sulfate CCN concentration.

In an effort to generalize our approach in the development of microphysical parameterizations, we are exploring microphysical feedbacks and parameterizations in warm rain cumuliform clouds. In order to accomplish this, we have expended significant effort to rewrite our LES model to run on distributed parallel computing architectures. Being able to take advantage of significant computational resources at our disposal, we are now able to resolve both fine scale mechanisms (stratocumulus entrainment, lateral entrainment in cumulus) and run on large enough domains to represent the mesoscale component of the circulation.

Finally, the recent proliferation of quality observational datasets invites rigorous verification of cloud microphysical parameterizations. However, the procedure of how to reconcile models and observations is not well understood. Typically lower order moments like mean or variance are compared; however, this is a fairly blunt tool that can mask important behavior in both models and observations. The approach we are exploring is one of analyzing and comparing PDFs of model and observational quantities, and comparing sensitivities of each to varying environmental conditions. Ideally, a parameterization would be able to produce not only an observed PDF but the observed sensitivity to other variables.

WORK COMPLETED

The following tasks are in progress:

1. Developing a parameterization of CCN activation for bulk microphysical models

2. Formulation and testing of a parameterization of giant CCN

3. Exploring aerosol-cloud-precipitation feedbacks and developing parameterizations for warm-rain cumulus

4. Verification of cloud microphysical parameterizations

Work has been completed on the following task:

1. Quantifying the processing of CCN by collision-coalescence in COAMPS

RESULTS

1. Parameterization of CCN activation

Classical theory predicts that CCN activate and nucleate droplets at or just above cloud base in buoyant updrafts where supersaturation is maximum. Representing the nucleation process in numerical models typically entails one of the following assumptions: constant droplet number concentration; a simple diagnostic relation between (N_c) and CCN concentration (N_{CCN}) (e.g. Mechem and Kogan 2003); or, a parcel model with detailed specification of aerosol parameters (Abdul-Razzak et al. 1998; Snider et al. 2003). From a conceptual point of view, physically based schemes are preferable since they can represent feedback of the model (gridscale or SGS) onto the nucleation process.

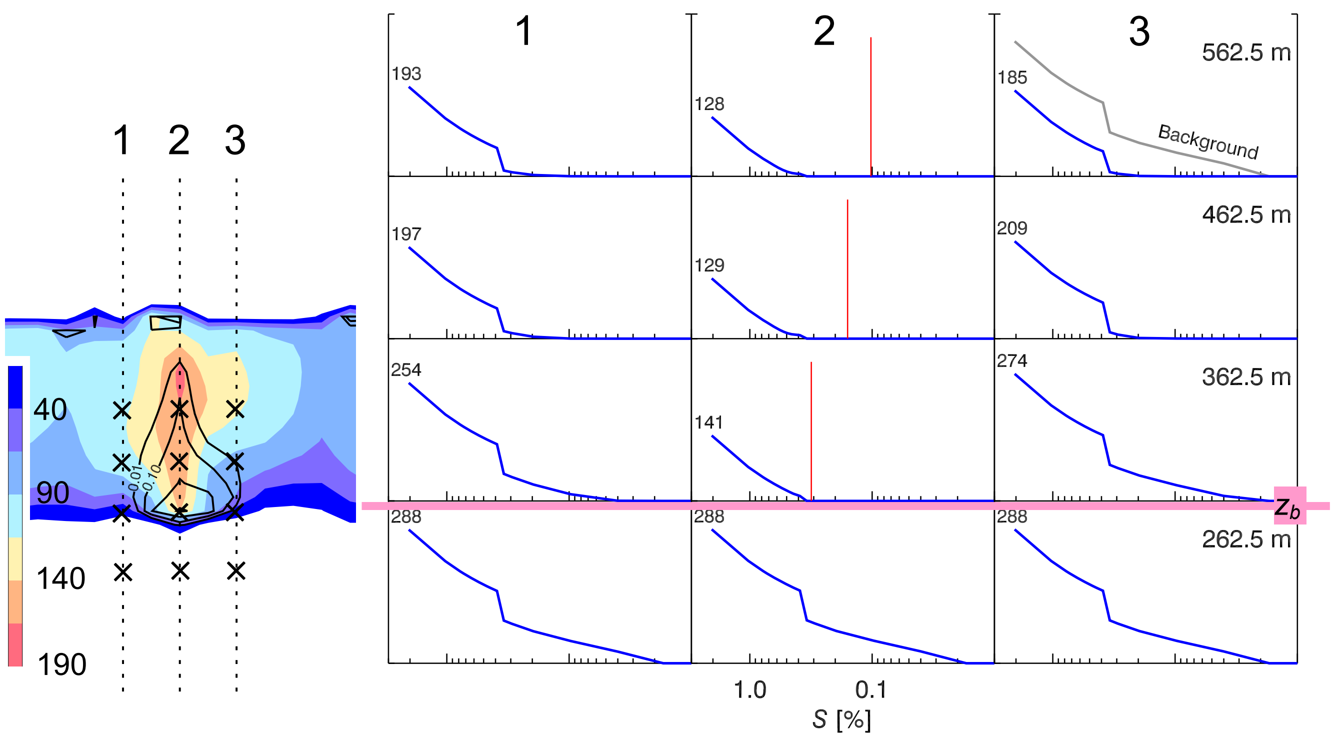

Figure 1. A vertical cross section of *supersaturation (black contours) and droplet concentration (filled contours, units of [cm^{-3}]) in a supersaturated updraft region. Cloud depth is approximately 350 m. Panels are CCN spectra in and adjacent to a supersaturated updraft core, taken from model grid points indicated by the "x" points in the left hand vertical cross section. Numbers indicate total CCN at each point, and red bars represent grid point supersaturation (if over 0.01%).*

[graph: Droplet concentration in updraft core increases with height, above the peak in low level supersaturation. Aerosol spectra at grid points adjacent to the updraft imply this results from entrainment of unactivated aerosol into the updraft.]

Recently, we have identified complications to classical theory of nucleation. Our complication is related to nucleation enhancements previously documented (Pinsky and Khain 2002; Phillips et al. 2005). Results from large eddy simulation suggest aspects of aerosol activation in marine

stratocumulus not captured by simple empirical relations or closed parcel models. Classical theory predicts that all of the droplet nucleation in Figure 1 should occur at cloud base, where supersaturation is a maximum. However, N_c plainly increases with height in column 2, with its maximum well above cloud base. The CCN spectra on either side of the updraft maximum appear to be key in explaining this increase. For a parcel rising in the updraft core (column 2), 140 cm^{-3} droplets are nucleated in the peak supersaturation region near cloud base. With supersaturation (S) decreasing with height, we would not expect the smaller bins to activate. However, the unactivated CCN in adjacent regions can be entrained into the buoyant updraft and then activated in the decreased supersaturation field above the peak in S. In this manner, N_c can increase with height in the updraft while S decreases with height.

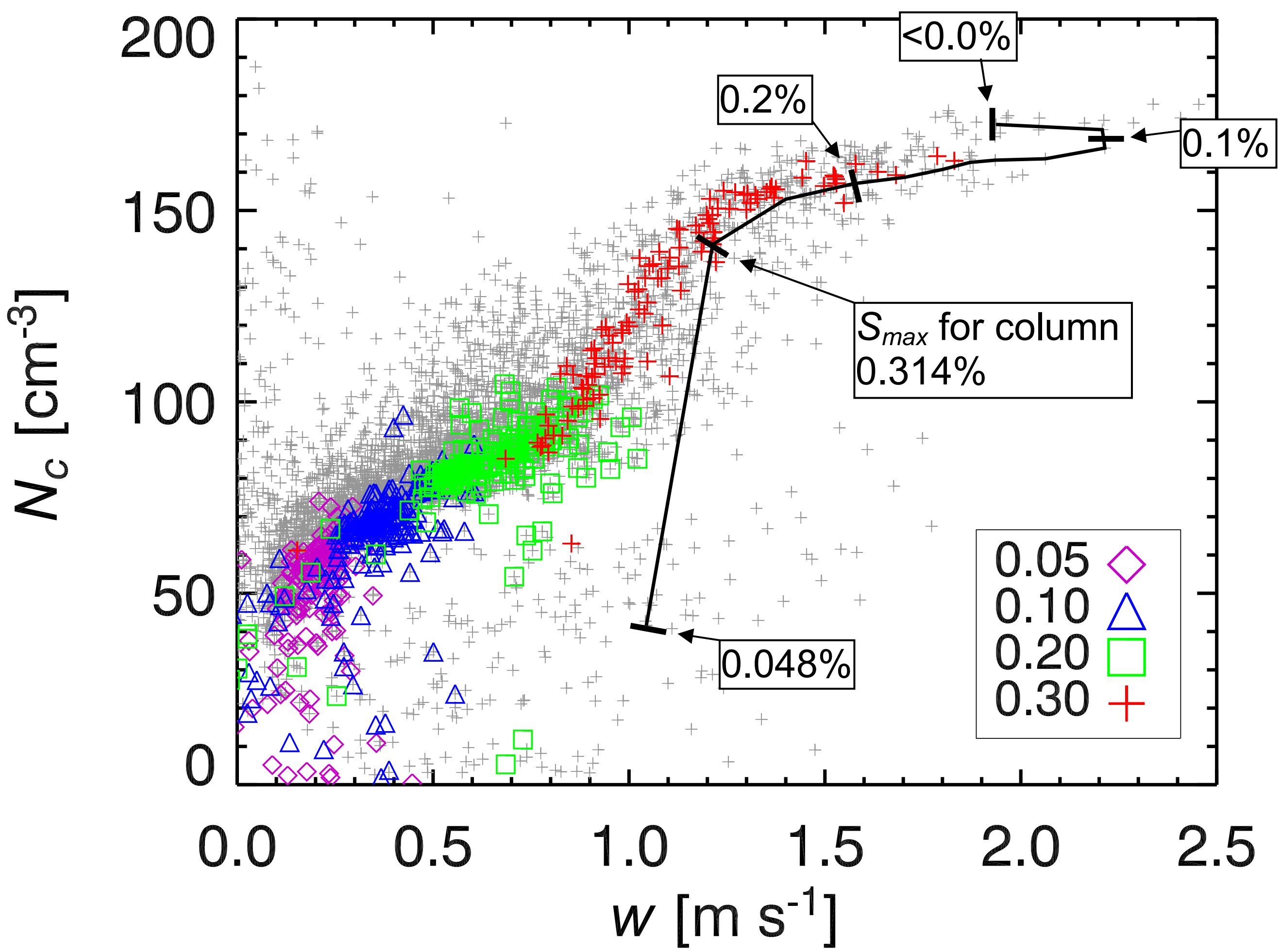

Figure 2. Scatterplot of cloud base droplet concentration as a function of vertical velocity, stratified according to supersaturation. Gray marks represent supersaturated regions above cloud base. The dark black line represents the updraft core.

[graph: Droplet number is well correlated with vertical velocity, especially over supersaturated cloud base regions. The relationship if more complicated when the analysis includes all supersaturated regions. For the updraft core, a large jump in droplet concentration corresponds to the primary nucleation event at cloud base. Above this, droplet concentration continues to increase, up to the level where supersaturation finally drops below 0.1%.]

Over supersaturated updraft regions, droplet concentration is well correlated with updraft (Fig. 2), though the relationship becomes more complicated when generalized to all supersaturated regions. Initially, the relationship between N_c and w for an updraft core (black line in Fig. 2) reflects the "classical" behavior — the large increase in droplet concentration corresponding to the primary nucleation event at cloud base. However, for this parcel, N_c continues to increase, up to the level where S finally decreases below 0.1%. This profile illustrates that simply accounting for the nucleation associated with the peak supersaturation does not give a complete picture of the nucleation process. The neglect of this additional nucleation of droplets could conceivably lead to an underestimate of N_c. Since nucleation does not occur uniformly but rather only in supersaturated updrafts, the number of CCN activated should be considered an upper bound on grid-mean droplet concentration. Clearly a non-entraining adiabatic model cannot capture this continuous activation, though including an entrainment term in a 1D model may be able to represent this process for cases of low cloud fraction, where the concepts of parcel and environment are well posed.

2. Parameterization of giant CCN

Giant CCN (GCCN; $1<r<10$ μm) have been suggested as a mechanism to develop precipitation nuclei in the size range of ~20-25 μm, which is considered the bottleneck in classic theory of warm rain formation. Our previous work has demonstrated that a minimum of three aerosol categories should be considered: total CCN concentration, concentration of Aitken nuclei, and GCCN. The GCCN parameterization formulated in last year's annual report exhibits the expected sensitivity of boundary layer properties to GCCN and background sulfate concentrations. Sensitivity to GCCN is most apparent for highly polluted background aerosol loads and leads to boundary layer decoupling, reduced liquid water content and droplet concentrations, and enhanced drizzle rates.

Evaluation of the influence of GCCN on cloud system radiative properties constitutes an additional test of the parameterization. Our analysis is similar to that of Feingold et al. (1999). The effect on radiative properties of adding various concentrations of GCCN to background clean and polluted cases of CCN is summarized in Fig. 3. GCCN has little effect on the optical properties for the clean cases, largely because they are already drizzling. Adding GCCN to the polluted case, on the other hand, results in noticeable reductions in optical depth and albedo. The reduction in optical depth and albedo results from a reduction in cloud liquid water content (from drizzle loss) and a decrease in droplet concentration accompanying drizzle production (collection). Less liquid water spread out over fewer droplets decreases the backscatter cross section and the optical depth. Absolute susceptibility varies little over the GCCN concentration, mainly for the reason that the relative difference in droplet number between the simulations is quite small. The response of albedo to changes in droplet concentration is smaller in the polluted case. In other words, equivalent changes in N produce more albedo response in the clean case (small N) than in the highly polluted case (large N). Yet Figs. 3a and b plainly demonstrate that the polluted case is more sensitive to the addition of GCCN. For this reason, susceptibility relative to the control simulations (Fig. 3d) most aptly illustrates the sensitivity of albedo to change in droplet number. As expected, the relative susceptibility of the polluted case is much greater than that of the clean case, and increases with increasing GCCN. These results are consistent with previous simulations employing explicit microphysical methods (Feingold et al. 1999) and increase our confidence of the fidelity of the GCCN parameterization when it is implemented into COAMPS.

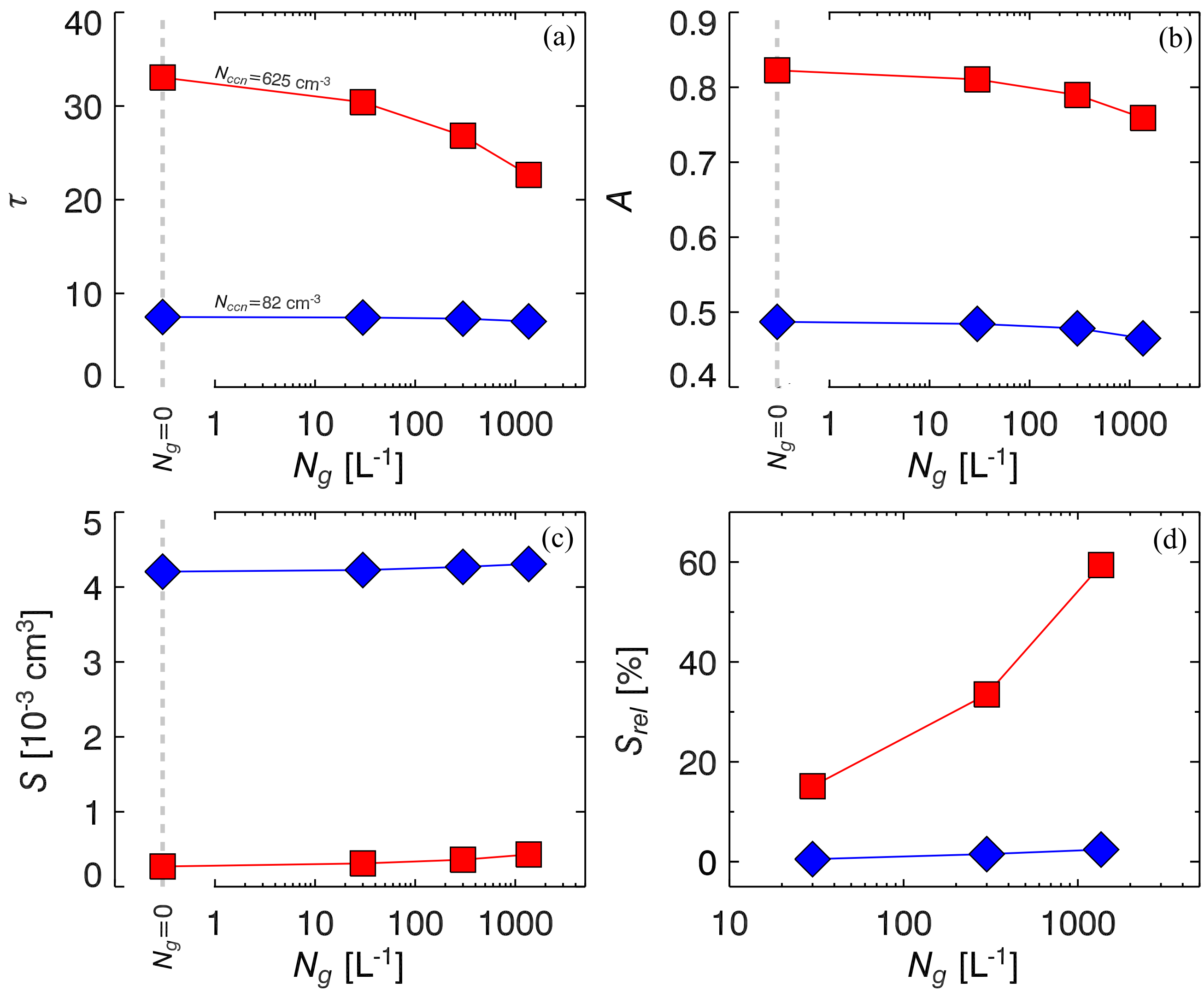

Figure 3. Hourly domain-mean calculations (2-3 h) of radiative quantities for clean (blue) and polluted (red) simulation series. (a) Optical depth; (b) Albedo; (c) Susceptibility [A(1-A)/(3N)]; (d) Susceptibility relative to the control simulations without GCCN.

[graph: For the polluted simulation series, optical depth and albedo decrease with increasing GCCN concentration. The clean series shows little sensitivity to GCCN. Susceptibility of albedo to a change in droplet number is large for the clean simulations and small for the polluted cases. Susceptibility relative to the control simulations is large in the polluted case and increases with GCCN concentration.]

3. Generalizing aerosol-cloud feedbacks and developing parameterizations for warm-rain cumulus

Our past efforts in developing microphysical parameterizations concentrated on boundary layer stratocumulus. We are expanding and generalizing our techniques in order to explore microphysical sensitivities of aerosol-cloud-precipitation processes in warm rain cumulus. Investigating these clouds necessitates simultaneously a fine grid spacing and a large domain; these are particularly

computationally intensive constraints when employing size-resolved microphysics. To this end, we have expended significant effort to rewrite our LES model to run on distributed parallel computing architectures using the message passing interface (MPI). Being able to take advantage of significant computational resources at our disposal, we will be able to resolve both fine scale mechanisms (stratocumulus entrainment; lateral entrainment in cumulus) as well as be able to run on large enough domains to represent the mesoscale component of the circulation.

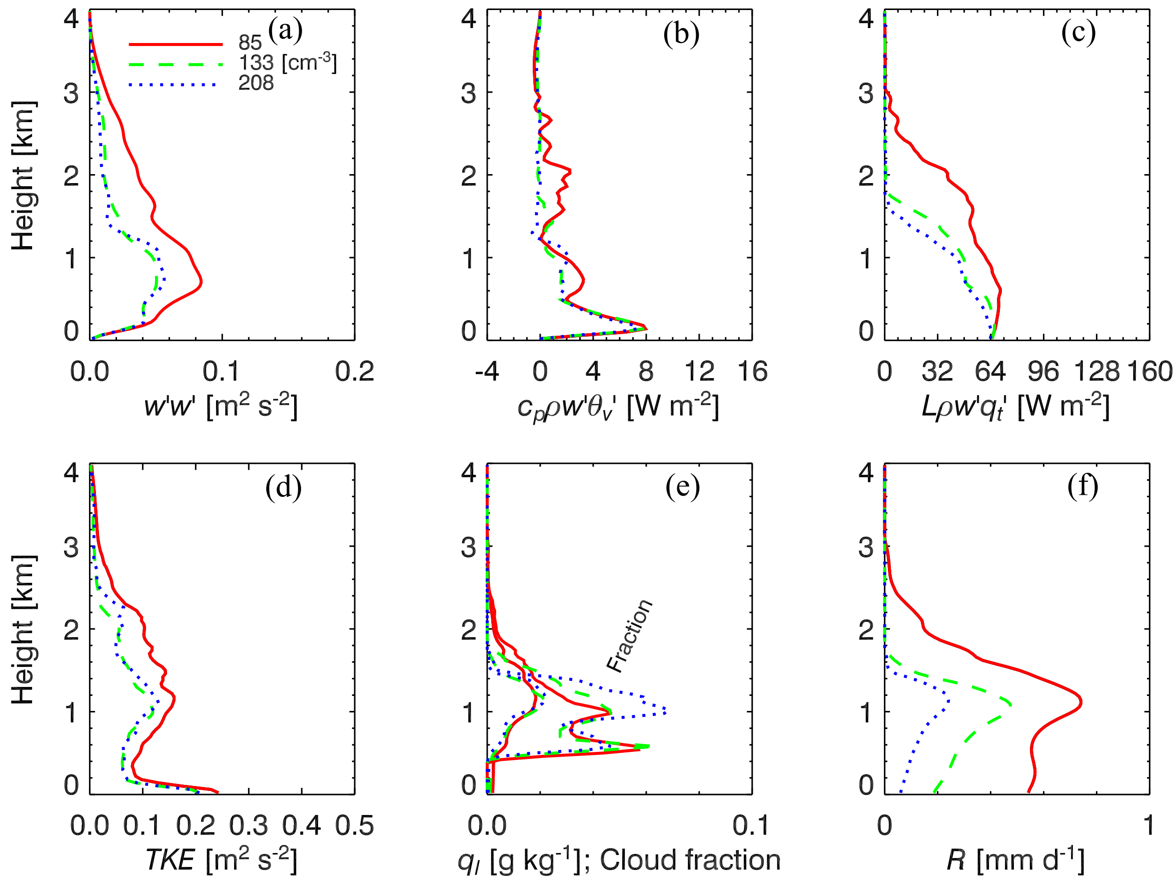

Figure 4. Vertical mean profiles for three RICO cumulus cases with indicated initial aerosol concentrations. (a) Vertical velocity variance; (b) Buoyancy flux (resolved); (c) Total water flux; (d) TKE; (e) Liquid water and cloud fraction; (f) Precipitation rate.

[graph: Cloud structure, turbulence properties, and precipitation are all sensitive to the initial CCN properties. Lower CCN concentration is associated with enhanced precipitation and deeper, more vigorous cloud structures. The secondary maximum in cloud fraction associated with detrainment tends to be enhanced at larger CCN concentrations.]

Preliminary results for a simulation of precipitating trade cumulus from the Rain in Cumulus over the Ocean (RICO) field project indicate significant sensitivity of the cloud system and turbulence properties to changes in ambient aerosol (Fig. 4). Stronger cloud dynamics and larger drops relative to our previous stratocumulus simulations necessitate expanding from 25 to 34 droplet size categories. Lower values of CCN are associated with enhanced precipitation (Fig. 4f) and deeper, more energetic cloud updraft cores (Figs 4a and d). A tendency of the more polluted cases to produce enhanced cloud

coverage in the detrainment region is noted (Fig. 4e) and is reminiscent of a commonly studied case from ATEX (Atlantic Tradewind Experiment; Stevens et al. 2001), where cumulus were rising into a layer of stratus. Precipitation efficiency may be deduced by the varying drizzle rates, the largest being ~25% (0.55 mm d^{-1} drizzle rate and a latent heat flux of 64 W m^{-2}).

4. Verification of cloud microphysics parameterizations

Recently, new advanced techniques have been developed for examining the structure of stratus clouds based on 3-mm wavelength Doppler radars using very fast processing systems (Kollias and Albrecht 2000). The W-band Cloud Radar at the Atmospheric Radiation Measurement Program Southern Great Plains (ARM SGP) site Climate Research Facility is capable of providing 30-m vertical resolution with a 2-s time sampling rate. These high resolution observational data sets are consistent with those produced in large eddy simulation. Kollias and Albrecht refer to this novel technique as "Large-Eddy Observations in support of Large Eddy Simulations *(LEO for LES)"*. The question arises of how most efficiently to utilize opportunities provided by new cloud radars for the verification of LES models and microphysical parameterizations derived from LES data. The traditional method of model verification is to compare the first and, in some cases, the second moments of predicted and observed cloud parameters. A more robust approach is to compare PDFs of model and observational variables and study their dependence on environmental conditions.

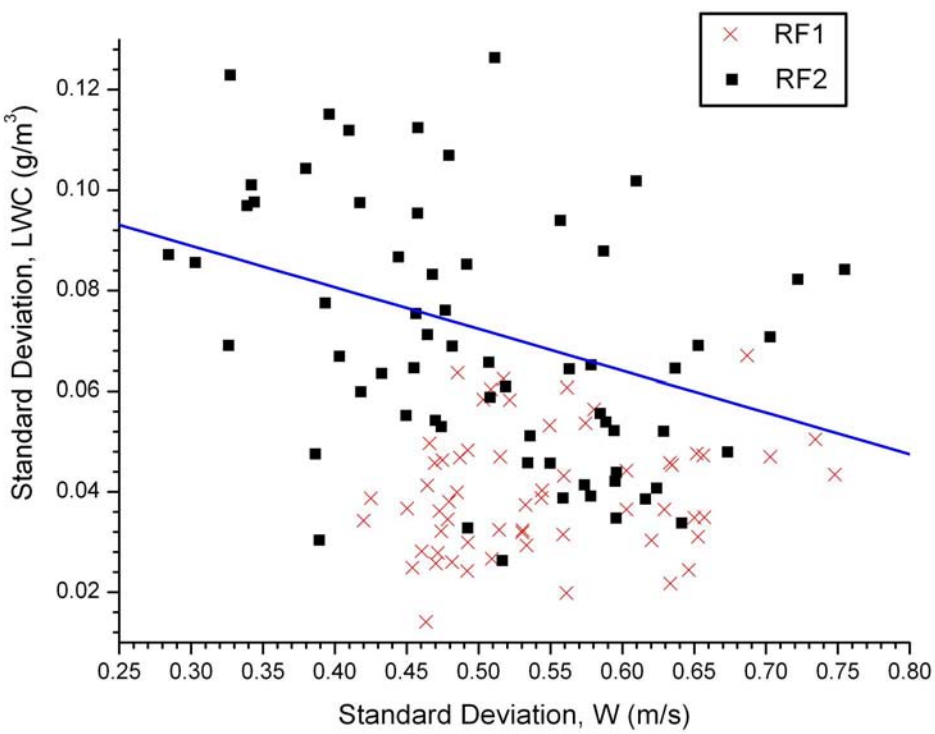

Figure 5. The dependence of LWC standard deviation on the intensity of turbulence expressed by the vertical velocity standard deviation. Crosses and squares denote data from DYCOMS flights in non-precipitating stratocumulus (RF01) and precipitating (RF02) stratocumulus clouds. The blue line represent best linear fit to the RF02 data.

[graph: the standard deviation of LWC is smaller (more homogeneity) in non-precipitating conditions (RF01), while LWC standard deviation decreases with increasing turbulence in precipitating clouds (RF02).]

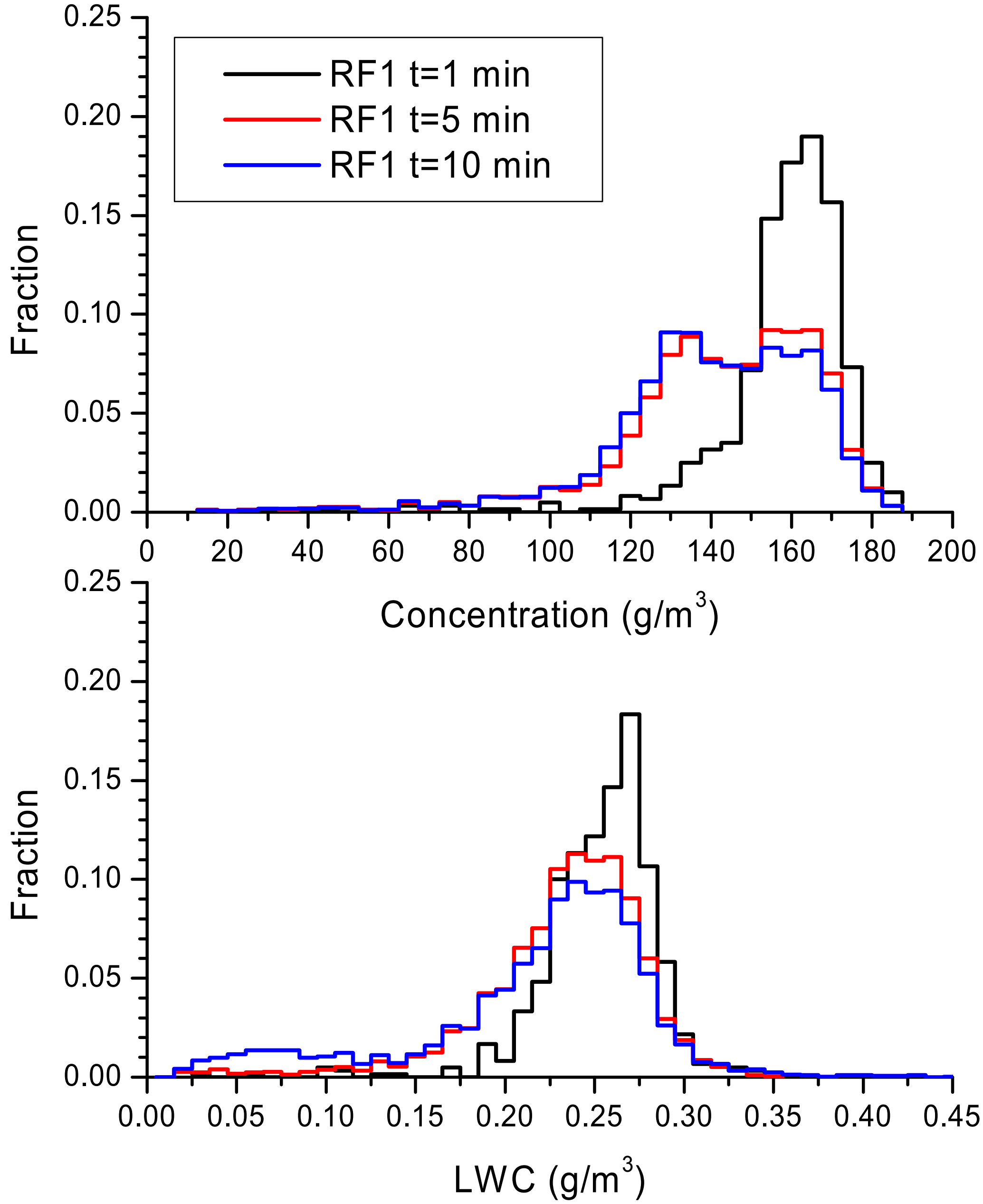

Figure 6. Scale dependence of the PDF of liquid water content and drop concentration based on data from the DYCOMS flight RF1 in non-precipitating stratocumulus cloud. The time scales of 1, 5, and 10 min translate to the spatial scales of approximately 6, 30 and 60 km.

[graph: In relatively homogeneous non-precipitating Sc the LWC is less variable than drop concentration which has to be noted in model comparison with observations.]

Exploring various details of comparisons based on PDF approach is the topic of the thesis work by OU MS student Danielle Corrao. Specifically, we have studied PDFs of cloud liquid water and drop concentration during two research flights (RF01 and RF02) conducted during the DYCOMS-II field project. The study revealed that PDFs in non-precipitating clouds (RF01) differ significantly from PDF in precipitating clouds, as Fig. 5 demonstrates. PDF width is dependent on the intensity of turbulence

in precipitating clouds but rather insensitive to it in non-precipitating conditions. The latter reflects the fact that non-precipitating stratocumulus are more homogeneous. PDFs plotted in Fig. 5 are calculated over a length scale of ~6000 m, which is roughly the domain size of LES. PDFs in Fig. 6, however, demonstrate strong scale dependence which needs to be taken into consideration when comparing LES model results with observations. Accounting for this scale dependence is also important in representing model subgrid variability in calculations of unbiased microphysical process rates (Kogan et al. 2005). The results of the study will lead to the development of more robust techniques of model and parameterization verification.

5. Coalescence processing of CCN in COAMPS

Results from our investigation of aerosol-cloud-precipitation interactions in COAMPS using the CIMMS bulk drizzle parameterization were recently published in Mechem et al. (2006). COAMPS was employed to explore the relative importance of source, sink, and transport processes in producing an accurate forecast of the boundary layer aerosol-cloud-drizzle system. The reduction of CCN by cloud processing is not uniquely related to total particle concentration; rather, the behavior of cloud processing suggests relationships (scalings) based on cloud base drizzle rate (R) and droplet concentration (N_c). Cloud processing is found to be correlated with drizzle, a relationship that can be expressed as a power law for drizzle rates less than 0.6 mm d^{-1}. A scaling for cloud processing based on the product of N_c and R is accurate over a wider range of drizzle rates (Fig. 7). Results from LES with size-resolved microphysics demonstrate reasonable agreement with COAMPS and the two parameter scaling.

Entrainment plays an important role in strongly modulating the mean marine boundary layer (MBL) concentration, both increasing and decreasing CCN, depending upon the entrainment velocity w_e and the difference between MBL and free tropospheric CCN concentrations. The importance of entrainment suggests that transport processes, especially in the vertical, play a fundamental role in the overall MBL CCN balance. In situ source rates of CCN, taken to represent heterogeneous chemical processes and sea salt flux of submicron size particles from the ocean surface, must be unrealistically large in order to be of the same magnitude as cloud processing. Because of the prevailing importance of cloud processing and entrainment over timescales of a typical mesoscale forecast (6-48 h), the results indicate that incorporating accurate vertical aerosol profiles into the model update cycles, either from remote sensing or from global chemistry models, is more important than highly constrained local CCN source rates.

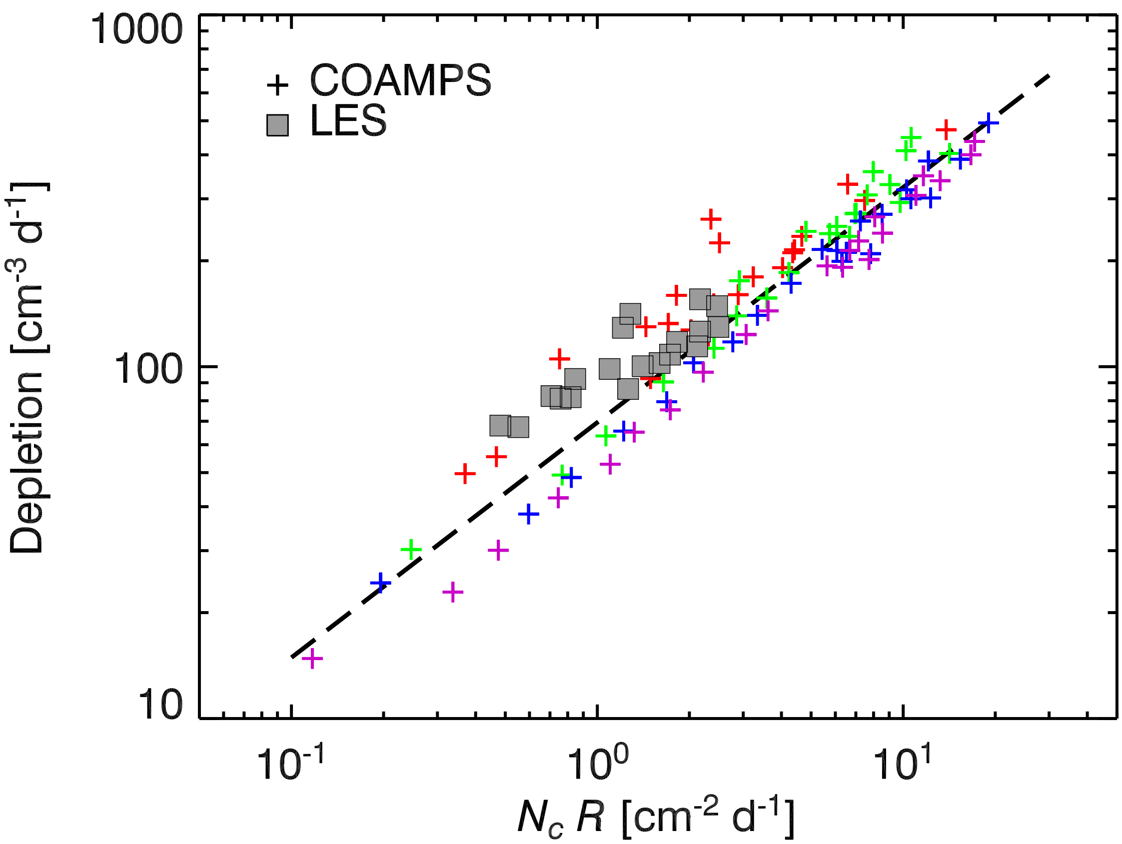

Figure 7. Scaling for MBL-mean CCN depletion for four COAMPS simulations (crosses) and an LES simulation (filled rectangles). Crosses are colored to indicate initial CCN concentrations of 100 (red), 200 (green), 400 (blue), and 800 (magenta) cm^{-3}. Dashed line represents a best fit to the COAMPS data of $D = 69.4(N_c R)^{0.668}$, where N_c and R are expressed as cm^{-3} and cm d^{-1}, respectively.
[graph: MBL-mean CCN depletion for COAMPS and LES simulations is well correlated with the product of droplet concentration and drizzle rate.]

IMPACT/APPLICATIONS

Improved parameterization of cloud physical processes will result in more accurate numerical weather prediction for U.S. Navy operations. Current results are relevant to more accurate forecasts of cloud persistence and radiative parameters.

TRANSITIONS

Future improvements to the COAMPS cloud physics parameterization package (activation parameterization, giant CCN parameterization) developed at CIMMS/OU will be made available to NRL and registered COAMPS users at large. Our results have been disseminated to the science community at five conferences and by publication in two major refereed journals and conference proceedings (total of 11 papers).

RELATED PROJECTS

We are using our participation in the GCSS (GEWEX Cloud Systems Study) RICO (Rain in Cumulus over the Ocean) study to generalize these techniques to more cumuliform low cloud systems. Our participation in the ARM program greatly enhances the verification component of our work detailed in Section 4.

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